

CURRENT STATUS OF THIN FILM (Ba,Sr)TiO₃ TUNABLE MICROWAVE COMPONENTS FOR RF COMMUNICATIONS

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The performance of proof-of-concept ferroelectric microwave devices has been moving steadily closer to the level needed for satellite and other rf communications applications. This paper will review recent progress at NASA Glenn in developing thin film Ba_xSr_{1-x}TiO₃ tunable microwave components for these applications. Phase shifters for phased array antennas, tunable filters and tunable oscillators employing microstrip and coupled microstrip configurations will be presented. Tunabilities, maximum dielectric constants, and phase shifter parameters will be discussed (e.g., coupled microstrip phase shifters with phase shift over 200° at 18 GHz and a figure of merit of 74.3°/dB). Issues of post-annealing, Mn-doping and Ba_xSr_{1-x}TiO₃ growth on sapphire and alumina substrates will be covered. The challenges of incorporating these devices into larger systems, such as yield, variability in phase shift and insertion loss, and protective coatings will also be addressed.

Keywords: Ba_xSr_{1-x}TiO₃ thin films; phase shifters; tunable resonators, Ku- and K-band frequencies; MgO and LaAlO₃ substrates

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I. INTRODUCTION

The exploding demand for broadband communications is driving systems higher in frequency, above the useful range of Si devices. Non-linear dielectric materials such as $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ (BST) may provide tunable microwave devices which are small, light-weight, planar and inexpensive. Varactors, tunable filters, tunable oscillators, phase shifters and phased array antennas are all potential applications of this technology. Tunable ferroelectric devices are generally used above the Curie temperature (T_c) in the paraelectric regime, where the large dielectric constant is tuned with an applied dc electric field. Hence for room temperature applications $\text{Ba}_x\text{Sr}_{1-x}\text{TiO}_3$ is typically used with $x < 0.7$, while SrTiO_3 (STO) is employed in cryogenic applications.

This paper briefly reviews the best results from NASA Glenn Research Center (GRC) from tunable ring resonators and tunable filters, then focuses on phase shifters intended for phased array antennas. All of the devices use a microstrip and/or coupled microstrip structure fabricated on top of laser ablated thin films of BST or STO. The film thickness ranges from 0.3 to 2.0 μm . All of the BST films discussed in this paper have Ba:Sr ratios of 50:50 or 60:40, with the exception of one 40:60 film. A cross sectional view of these structures is given in Fig. 1.

II. TUNABLE RESONATORS AND FILTERS

To illustrate the tuning available in these structures, consider the ring resonator structure in Fig. 2(a). The gray shaded region depicts where a 2.0 μm thick STO film is present on a substrate of 254 μm thick LaAlO_3 . The cross-hatched region shows where the 2.0 μm thick Au microstrip was fabricated. The tuning data for this structure at 77 K is given in Fig. 2(b). By applying a large dc voltage on the ring, $V_R = 491$ V, the resonant frequency of the ring is shifted up by 2 GHz (12% tuning) from its zero bias frequency of 15.26 GHz. Note that the sharpness of the resonance is only maintained by simultaneously biasing the gap between the ring and the microstrip line ($V_R - V_L$) to optimize the coupling. Values of $f_0/\Delta f_{3\text{dB}}$ as high as 15,000 were measured for this sample, where f_0 is the resonant frequency and $\Delta f_{3\text{dB}}$ is the width of the resonance 3 dB above the minimum. However, the loaded Q's only reached 50. Seven versions of these tunable ring resonators were fabricated using

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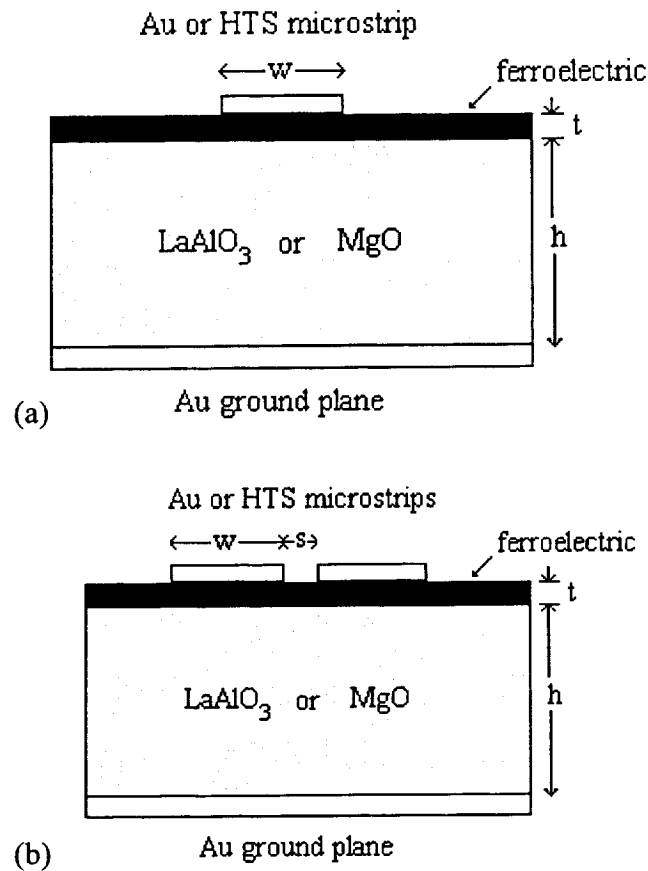


FIGURE 1 Cross sectional view of (a) microstrip and (b) coupled microstrip structures.

STO films with both YBa₂Cu₃O_{7-δ} and Au microstrips. More information on their design and measurement are published in [1].

Tunable microstrip filters have also been fabricated on thin STO and BST films on 254 μm LaAlO₃. These filters followed an edge-coupled design modified to accommodate the high dielectric constant film. Radial bias stubs were added to bring in the dc bias to each section. The best results from these filters were achieved at 30 K using YBa₂Cu₃O_{7-δ} microstrips on 300 nm thick STO films atop 254 μm thick LaAlO₃ substrates. A frequency tuning range of 12% around a center frequency of 17.8 GHz was measured, with a corresponding insertion loss in the passband of 1.5 to 3.0 dB.^[2] Two room temperature versions using Au and BST films demonstrated 4% tuning and 7 to 8.5 dB loss.^[3]

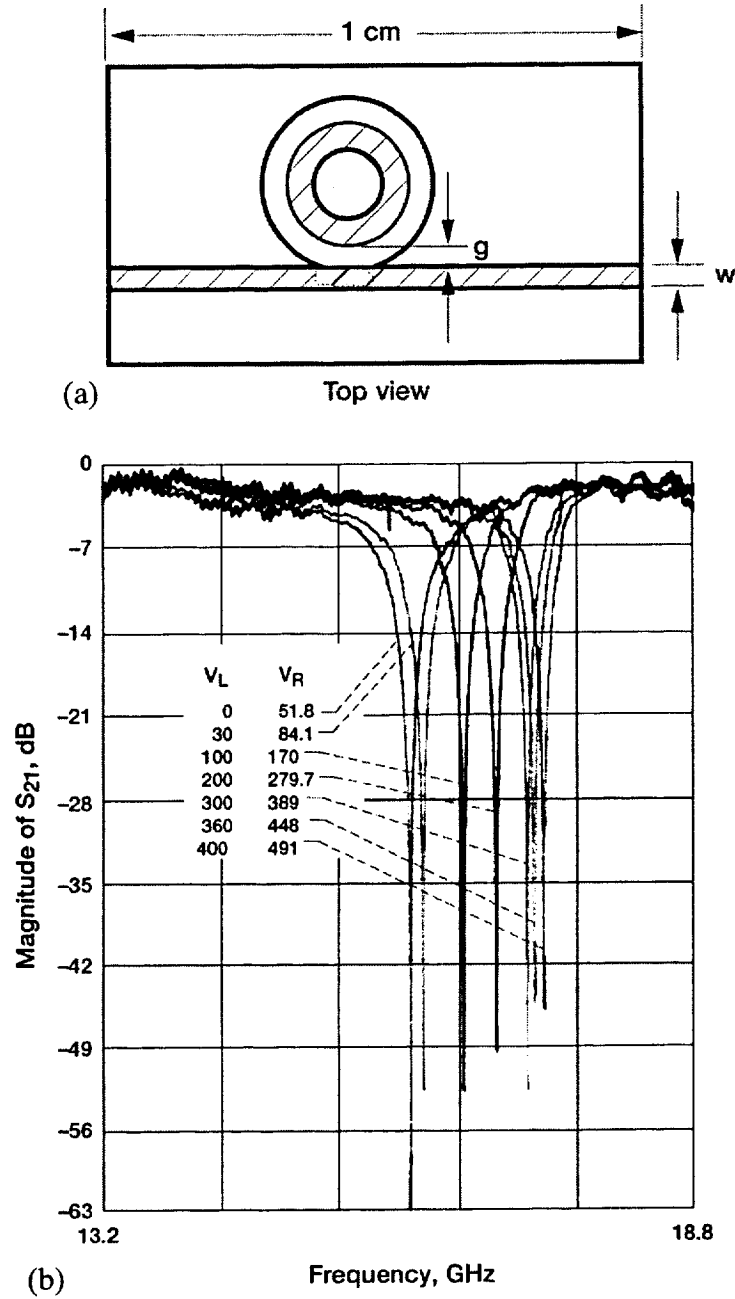


FIGURE 2 (a) Schematic of a tunable ring resonator. The ring width was 406 μm , outside diameter was 1694 μm , $g = 25 \mu\text{m}$ and $w = 89 \mu\text{m}$. The shaded region shows where the BST film resides. (b) Data from a Au(1.8 μm)/Cr(50 nm)/STO(2.0 μm)/LaAlO₃(254 μm) ring resonator at 77 K. The voltage on the ring, V_R , and line, V_L , are given.

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III. PHASE SHIFTERS

Our group has put much effort over the last several years into developing and improving room temperature phase shifters using coupled microstrips atop BST thin films. A typical configuration of these coupled microstrip phase shifters (CMPS) is shown in Fig. 3. The phase shifting elements are coupled microstrips separated by 7.5 to 10.0 μm . A dc bias of several hundred volts is applied across this gap. The radial stubs are present to apply the dc bias while minimally effecting the rf circuit. Multiple phase shifters are fabricated in series, separated by single microstrip sections. Each coupled microstrip section is a broadband single-pole passband filter as well as a phase shifter. As dc voltage is applied, the insertion phase shifts and the passband of the device shifts as well. Figure 4 shows the frequency dependence of the passband of a BST thin film phase shifter with eight coupled microstrip sections. As the dc bias is increased the passband shifts upward in frequency and narrows. The result is that these devices have a fairly constant insertion loss in a frequency bandwidth of about 10% of the operating frequency. The position of this useful frequency range depends upon dielectric constant of the film as a function of bias, the film thickness, and the maximal dc voltage.

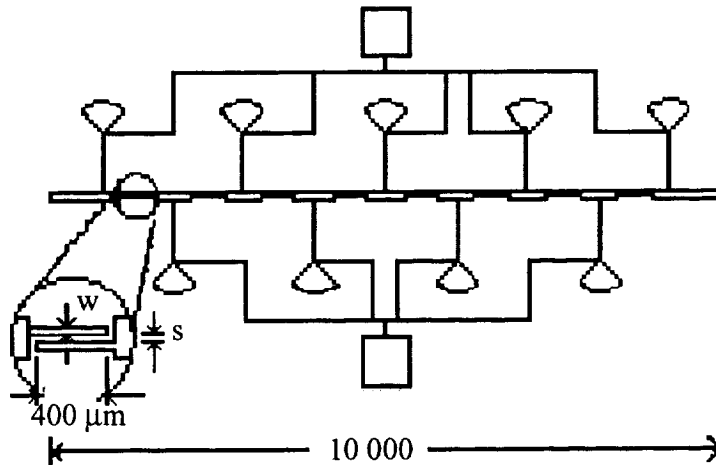


FIGURE 3 Schematic of an eight element CMPS on 254 μm thick LaAlO₃, $S = 7.5 \mu\text{m}$ and $W = 25 \mu\text{m}$.

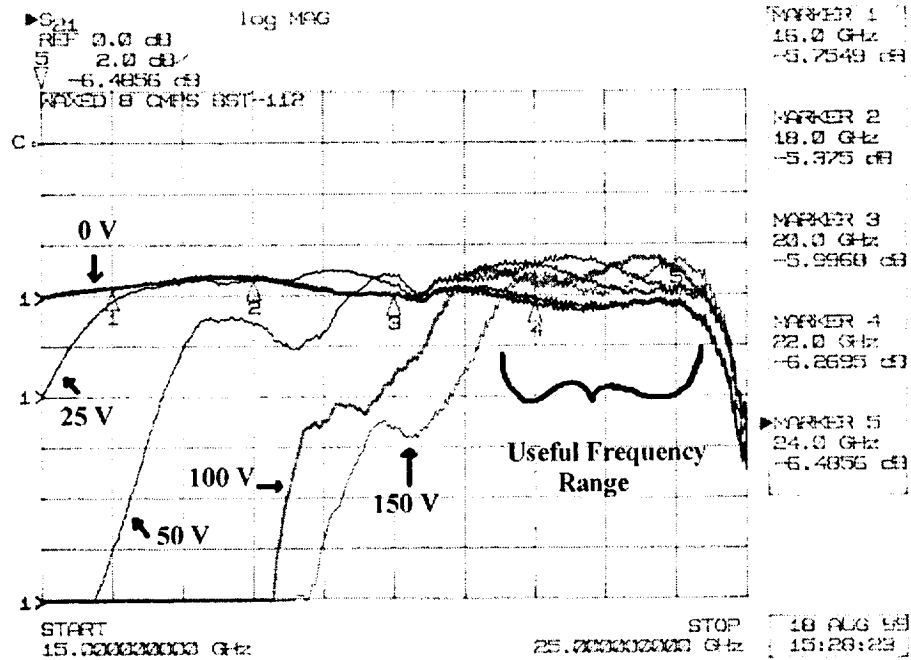


FIGURE 4 Frequency dependence of $|S_{21}|$ for an eight element Au(1.8 μm)/Cr(50 nm)/BST(400 nm)/MgO(312 μm) CMPS at 0, 25, 50, 100 and 150 V dc biases.

The early versions of CMPS were fabricated using STO films. All of these cryogenic devices were built on 254 μm thick LaAlO_3 substrates using the eight element design illustrated in Fig. 3. Both $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ and Au microstrips were tested. As with the tunable filters, a $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ circuit on a 1 μm thick STO film demonstrated the best results at 40 K and 16 GHz, showing 484° phase shift with 375 V dc bias.^[4] The maximum insertion loss was 6 dB, yielding a figure of merit, K , of $80^\circ/\text{dB}$ phase shift per maximum loss.

The same eight section CMPS design on 254 μm thick LaAlO_3 substrates was tested using thin films of BST. Film thicknesses between 300 and 1400 nm were tested. Phase shifter performance was compared with XRD analysis of the BST films. The highest K values of 50 to $55^\circ/\text{dB}$ achieved were obtained using BST films of 300-400 nm thickness which exhibited about 200° of phase shift. Increasing film thickness beyond 400 nm generally decreased the K value of the phase shifter.^[5] However, annealing at 1100°C in oxygen apparently increased the K value of a 750 nm thick film to $43^\circ/\text{dB}$ with 300° of phase shift. These

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phase shifters showed high correlation between crystallinity value (as deduced from XRD measurements) and tunability, and moderate correlation between crystallinity and phase shifter K .

A second CMPS circuit was then designed for BST films deposited on 508 μm thick MgO substrates. The motivation for moving to MgO substrates was the lower dielectric constant of MgO, 9.8, compared to 24 in LaAlO₃. The change allowed for wider microstrip lines with lower conductor losses. This new design employed coupled sections of length = 457 μm , width = 56 μm , and gap = 10 μm . However, this substrate necessitated larger radial bias stubs, reducing the number of CMPS sections to four in a 1 cm long sample. This design achieved slightly higher K values of 58.4°/dB but lower phase shifts with a maximum of 114° per 4 element phase shifter.

The K values of all of the CMPS phase shifters fabricated using laser ablated BST samples are shown in Fig. 5. The x coordinate is the design type. The original eight section design on LaAlO₃ is shown at $x=1$. The second design of four sections on 508 μm MgO is shown at $x=2$. The frequency at which each design typically operated best is given below the data. These frequencies are the average of each set. The optimal frequency for a particular sample might vary by as much as 3 GHz from this value depending on film thickness and dielectric properties. The data show a large amount of variation but one must note that these data includes samples with a wide variety of film thicknesses, dielectric properties and even institutions at which they were deposited. If one concentrated on depositing the same type of film, the variation can be greatly reduced.

The third column ($x=3$) of Fig. 5 is data for the next design of four CMPS sections that was fabricated on 312 μm MgO substrates. Here the coupled sections are 356 μm long, 25 μm wide, and 10 μm apart. This design has demonstrated the largest K values, up to 74.3°/dB. Figure 6 shows phase shift and insertion loss data for the best sample in reflection mode (i.e. one end open). Designs 2 and 3 both include samples which were doped with 1% Mn which are denoted by closed symbols. These eight samples show (with one exception) better performance than their undoped counterparts. The Mn doping is known to reduce microwave loss in these films without reducing room temperature tuning significantly.^[7] Another contributing factor may be that the MgO substrate designs favor lower dielectric constant BST films according to electromagnetic simulator modeling. For instance, a typical simulation of the

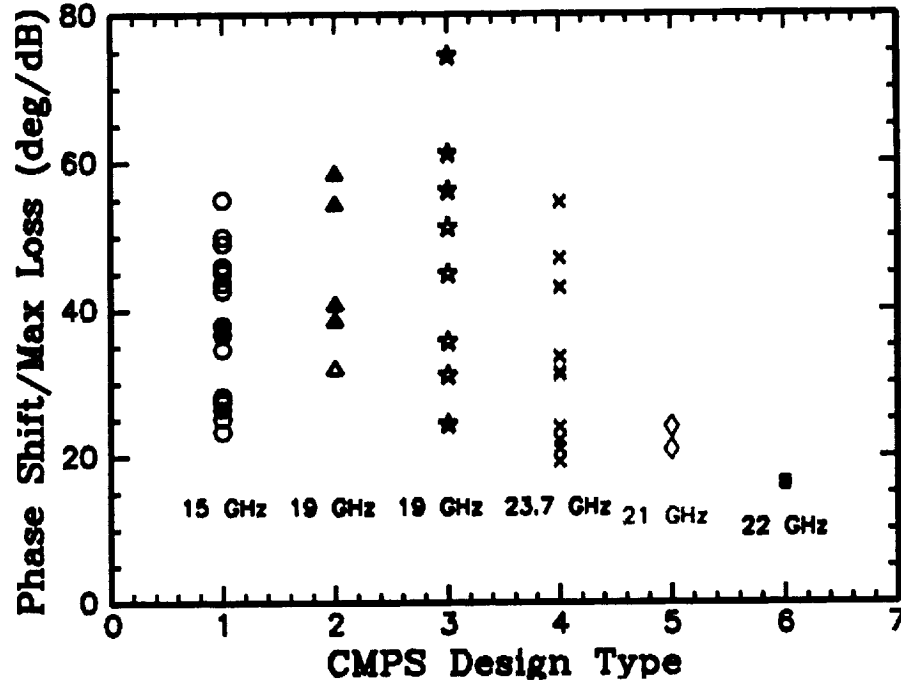


FIGURE 5 Room temperature K values for many CMPS of various designs. The ordinates are (1) 8 section on 254 μm LaAlO_3 (2) 4 section on 508 μm MgO (3) 4 section on 312 μm MgO (4) BST mesa-etched 8 section on 312 μm MgO (5) 4 section on 254 μm r-plane sapphire (6) 4 section on 254 μm alumina.

312 μm MgO design finds that in the region of $300 < \epsilon_r(\text{BST}) < 500$, the CMPS phase shift, $\Delta\phi \propto \epsilon^{1.0}$, while in the region $1000 < \epsilon_r(\text{BST}) < 1500$, $\Delta\phi \propto \epsilon^{0.52}$. This modeling agrees with the observation that, in contrast to the LaAlO_3 substrate case, the MgO substrate phase shifters do not show any positive correlation between K and XRD crystalline quality measurements, despite the fact that substantially higher tunabilities are observed using films with high crystalline quality.

The fourth data column in Fig. 5 shows data from an eight section design on a 312 μm MgO substrate intended for use in a small linear phased array antenna. These phase shifters have the same coupled section dimensions as type 3 but the BST film in these devices was etched so that only 430 μm wide strips centered on the CMPS devices remained. This etching was done to remove spurious tuning and loss under the biasing network. Another difference about the data in column 4 is that all

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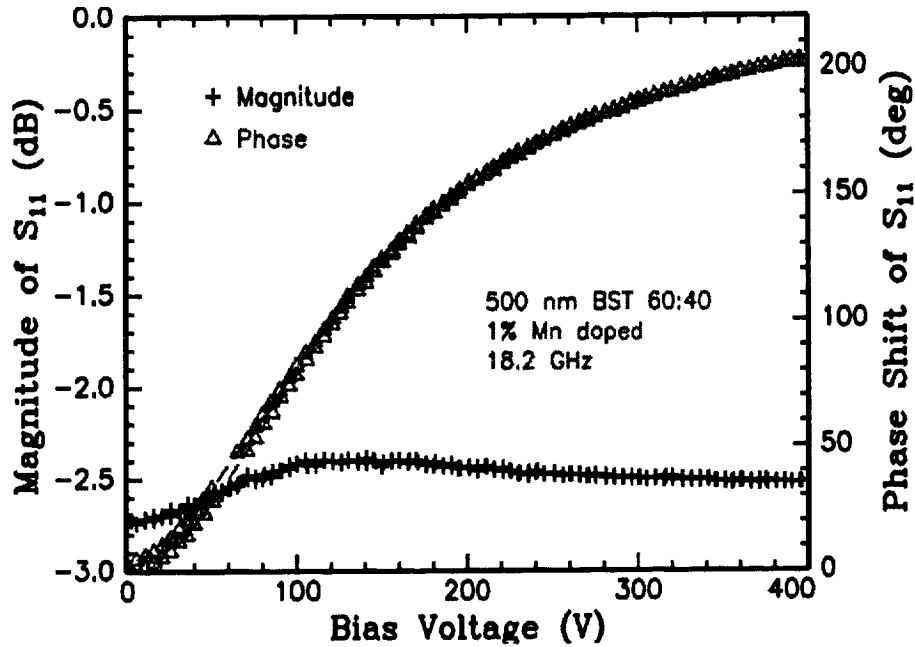


FIGURE 6 Phase shift and magnitude of S_{21} at 18.2 GHz and 300 K on a Au(1.8 μm)/BST (400 nm)/312 μm MgO CMPS with the largest K value, 74.3°/dB.

of the phase shifters were measured at exactly 23.7 GHz, rather than the frequency of maximum K . These CMPS circuits were designed to be wire-bonded into an array, which made their measurement with launchers difficult and probably reduced the K values shown here.

The last two columns of Fig. 5 show two samples each using substrates of R-plane sapphire and alumina, both coated with 50 nm of CeO₂. The design employed was identical to type 3 on MgO substrates. Clearly these films have poorer performance than their MgO and LaAlO₃ counterparts and need more optimization.

We have assembled a linear direct transmit phased array antenna consisting 16 patches using the phase shifters shown in column four. Details and data from that area will be given in another publication.^[8] To assemble and test the array, we have worked on several challenges associated with testing and building such arrays. These challenges consisted of coating the CMPS circuits with materials to resist air breakdown, yield and reliability considerations, and dealing with the variation between samples of many laser-ablated BST films.

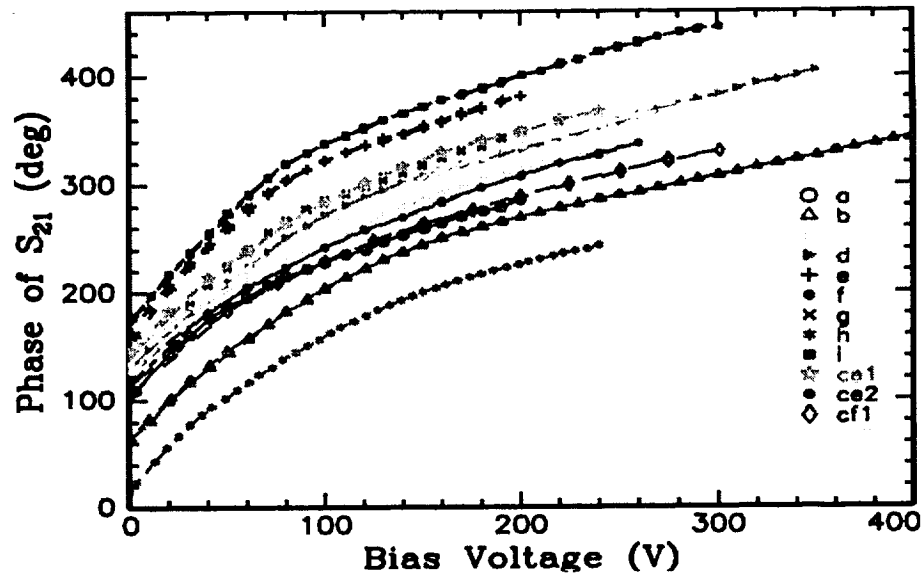


FIGURE 7 Phase of S_{21} data at 23.7 GHz and 300 K for 13 phase shifters of type 4.

Four coatings to prevent air breakdown were tested: sealing wax, sprayed teflon, sputtered SiO_2 and spun-on photoresist. The teflon failed completely, sputtered 500 nm thick SiO_2 worked in 1 of 2 samples, while the wax and photoresist both worked very reliably at applied electric fields as high as 50 V/ μm . These coatings generally caused a 0 – 0.2 dB decrease in the insertion loss. The improvements are due to both better matching and reduced radiation.

Yield becomes an important issue for building large arrays of CMPS circuits. Generally phase shifters break down when initially biased. We have observed that only about 1% of all samples tested will break down at voltages that they have previously survived. Breakdowns can occur in the BST film itself, or may be due to errors in the photolithography like spurs, or contaminants like dust on the surface. Of all of the laser ablated undoped BST phase shifters of designs 1, 2 and 3; 11% of the circuits broke down out of 36 tested. None of the 1% Mn doped BST samples have broken down out of 8 tested. This observation suggests that 1% Mn doping may increase the breakdown voltage or reliability of these circuits. Of the mesa-etched undoped BST phase shifters (type 4), 31% of these circuits broke down out of 15 tested. The extra processing may cause this increased failure rate. Another possibility is that the unetched circuit allows one to adjust the circuit position to avoid inho-

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mogeneities in the BST films, but the mesa-etched circuit does not. The issue of long-term reliability is covered in a separate publication.^[9]

Variation between phase shifters turned out to be a serious problem when building a phased array built from films deposited separately (i.e., in different runs). Figure 7 shows the phase of S_{21} as a function of applied bias voltage for 13 phase shifters of type 4. The data are not spread apart to distinguish curves; actual measured phase data are shown. While the curves have similar phase shifts and shapes, they are offset from one another. Phase shifters a – i had their BST (50:50) films deposited in the same laboratory to same thickness of 400 nm. Those samples did, however, have varied coatings of wax and photoresist, and also the difficult contact at one launcher. The resulting variation in phase forced each phase shifter to be measured and biased individually in the array. Samples ce1, ce2, cf1, and cf2 were deposited at a different laboratory. They have slightly different thicknesses, 475 nm for ce1 and ce2, 525 nm for cf1 and cf2.

This second set of samples, ce1, ce2, cf1 and cf2 were fabricated using an improved mask allowing easier testing using launchers. The phase and insertion loss data for these samples is given in Fig. 8. The variation between phases at a given voltage is reduced to about 50°, still a sizeable problem if all phase shifters need to be identical. The magnitude variation may actually be a worse problem. Figure 8(a). shows that the magnitude may vary by 4 dB between these phase shifters, causing large inaccuracies in the calculated phased array beam. One way around this difficulty may be to fabricate numerous phase shifters from a single larger area deposition. We have found in the two cases tested that samples diced out of a 2" diameter laser deposited wafer have had nearly identical microwave performances.

IV. CONCLUSION

Tunable (Ba,Sr)TiO₃ microwave components developed at NASA GRC have been reviewed. Tunable filters and resonators using microstrips and coupled microstrips of STO and BST thin films have been demonstrated with tuning ranges of 12% at Ku-band frequencies. Room temperature BST thin film on MgO coupled microstrip phase shifters have demonstrated performance as high as 74.3°/dB at 18 GHz. Coatings of wax and photoresist have proven adequate protection for these devices for

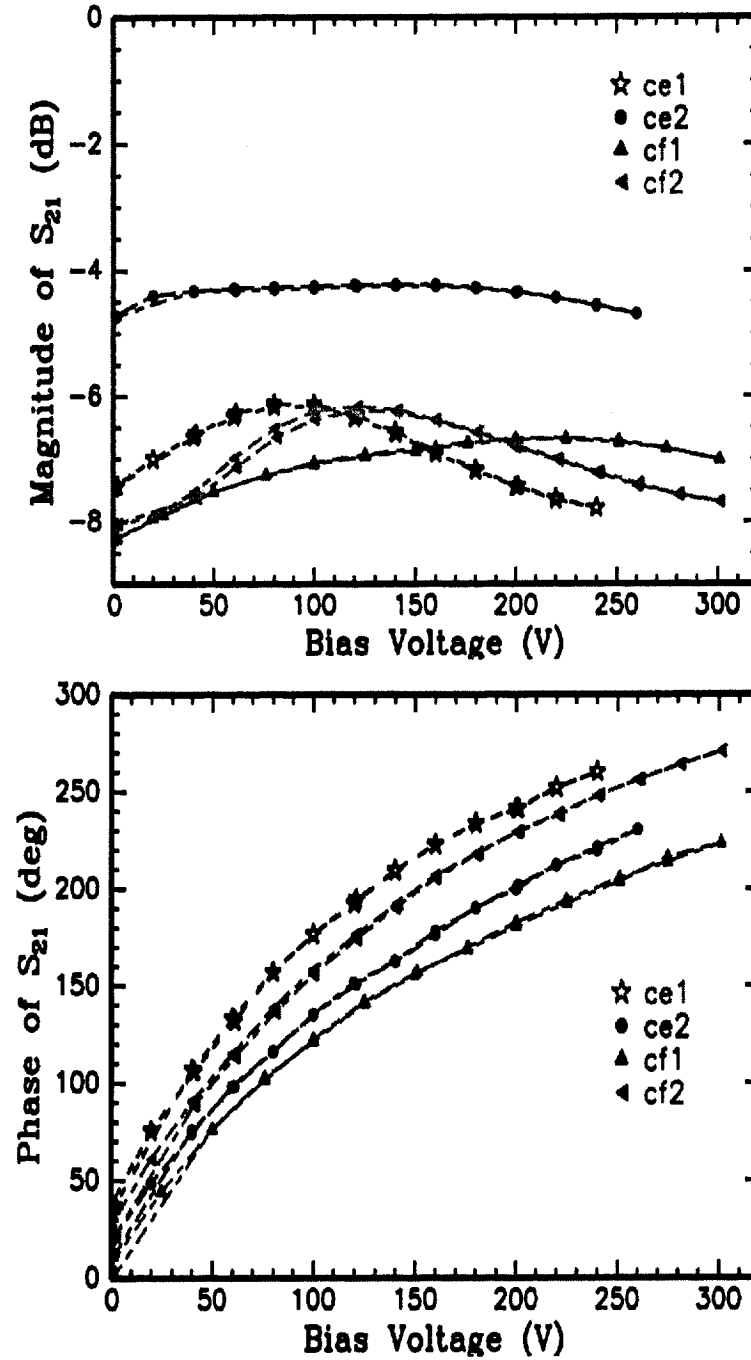


FIGURE 8 Phase and magnitude of S_{21} at 23.7 GHz and 300 K for 4 similar phase shifters of type 4.

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operation in air. Phase shifters prepared for phased array antennas by laser ablating films separately have shown large variations in phase shift and insertion loss. Dicing phase shifters out of larger area depositions may alleviate this problem.

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